

Exclusive two-charmonium vs. charmonium-gluon production at BELLE*

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We review the current theoretical situation with regard to the anomalously large cross section for exclusive $J/\psi + \eta_c$ production in e^+e^- annihilation, as measured by BELLE Collaboration.

I. INTRODUCTION

The J/ψ , a $J^{PC} = 1^{--}$ charmonium state, has, for many years, been a nice probe of hadron physics. Experimentally, it is easily detectable through its decay into a lepton pair. Theoretically, it has been a testing ground of perturbative quantum chromodynamics (QCD) because it involves both long and short-distance dynamics. Because of the separation between the long and short-distance scales involved in quarkonium dynamics, one can make use of nonrelativistic QCD (NRQCD) [1] to describe the production and decay of heavy quarkonium in a factorized form that is analogous with those in standard hard-scattering QCD factorization theorems [2–4]. The factorized formula is a linear combination of long-distance NRQCD matrix elements, which scale according to a known power of the velocity v of the quark inside a quarkonium in the meson rest frame. The matrix elements are determined by experimental measurements or, in some cases, through lattice calculations. Once the universal long-distance matrix elements are determined, one only needs to calculate the corresponding perturbative short-distance factors in order to predict the value of a physical observable.

As the first effective field theory for treating heavy quarkonium physics, NRQCD succeeded in providing infrared-finite predictions of the P -wave quarkonium decay rate [5] and presented a solution to the excessively large production rates for J/ψ and ψ' at large transverse momenta at the Tevatron [6]. These results were enough to rule out the color-singlet model [7], which had survived for decades. On the other hand, there are open questions still to be resolved in NRQCD phenomenology. One is the polarization of the J/ψ at large transverse momentum at the Tevatron: the CDF collaboration has not observed the large transverse polarization [8] at large transverse momentum that was expected from theoretical predictions [9–11]. However, the experimental data are not yet decisive. Experimental analyses with high-statistics, Run-II data are under way. On the theoretical side, large relativistic corrections have been found [12]. Furthermore, predictions have, so far, ignored spin-flip

interactions. Lattice calculations to estimate the importance of these interactions are being carried out [13].

Recently, quarkonium physics has been faced with two particularly difficult problems, both of which arise from BELLE measurements of J/ψ production in e^+e^- annihilation at $\sqrt{s} = 10.6$ GeV [14]. One production rate for inclusive $J/\psi + c\bar{c}$ relative to $J/\psi + X$ [14], which is much larger than predictions [15]. The other is the cross section [14] for the exclusive process $e^+e^- \rightarrow J/\psi + \eta_c$, which is larger than predictions by at least an order of magnitude [16, 17]. Both of them are the largest discrepancies that currently exist in the Standard Model.

In this proceeding, we review current theoretical status with regard to the exclusive problem. We first consider the original discrepancy between the data [14] and the theory [16] for exclusive $J/\psi + \eta_c$ production. Then we summarize two recently proposed scenarios to reduce the discrepancy between the data and the theory. One scenario is that the BELLE signal may contain double- J/ψ events [18, 19]. The other is a conjecture that the signal may include exclusive J/ψ production associated with a gluon [20].

II. EXCLUSIVE $J/\psi + \eta_c$ PRODUCTION

According to the NRQCD factorization formalism, exclusive processes of quarkonium production and decay, in which there is no other hadrons, should be described by the color-singlet model, up to corrections that are higher order in v . As in the simplest examples, such as electromagnetic annihilation decays and exclusive electromagnetic production processes, e^+e^- annihilation into exactly two charmonia should be accurately described by the color-singlet model, too. Because of the monoenergetic nature of a two-body final state, the absence of additional hadrons in the final state can be guaranteed experimentally. For many charmonia H , the NRQCD matrix element can be determined from the electromagnetic annihilation decay rate of either H or of another state that is related to H by the heavy-quark spin symmetry. Cross sections for exclusive two-charmonium production in e^+e^- annihilation can, therefore, be predicted, up to corrections that are suppressed by powers of v^2 , without any unknown phenomenological factors. In contrast inclusive quarkonium cross sections in hadroproduction involve several matrix elements whose values have large uncertainties.

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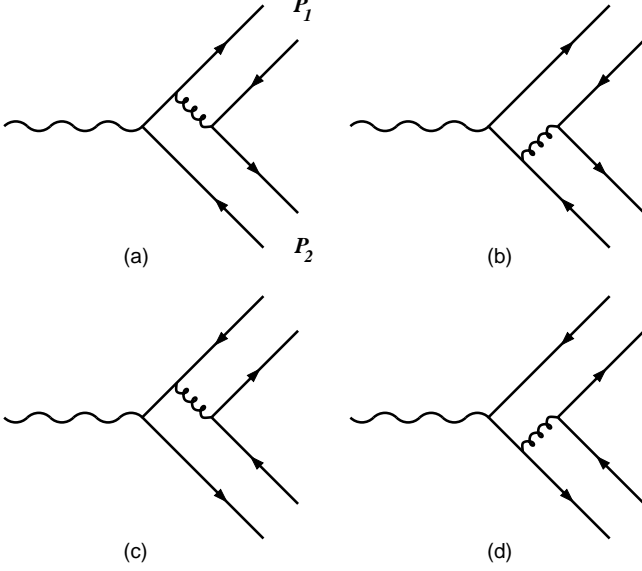


FIG. 1: QCD diagrams that can contribute to the color-singlet process $\gamma^* \rightarrow c\bar{c}_1 + c\bar{c}_1$.

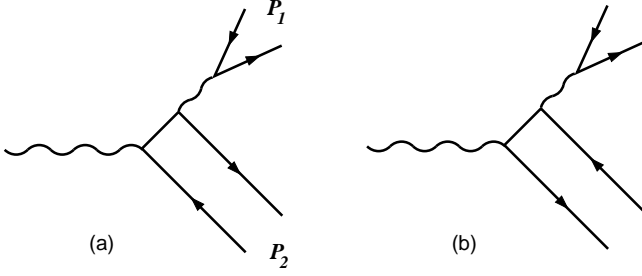


FIG. 2: QED diagrams that contribute to the color-singlet process $\gamma^* \rightarrow c\bar{c}_1(^3S_1) + c\bar{c}_1$.

Unfortunately, cross sections for exclusive two-charmonium production were too small to be measured until the newly built high-luminosity B factories collected large-statistics data. A naive estimate of the cross section for $J/\psi + \eta_c$ in units of the cross section for $\mu^+\mu^-$ is

$$R[J/\psi + \eta_c] \sim \alpha_s^2 \left(\frac{m_c v}{E_{\text{beam}}} \right)^6. \quad (1)$$

The two powers of α_s are the minimum needed to produce a $c\bar{c} + c\bar{c}$ final state. There is a factor of $(m_c v)^3$ associated with the wave function at the origin for each charmonium. These factors in the numerator are compensated by factors of the beam energy E_{beam} in the denominator, which yield a dimensionless ratio. As an example, consider e^+e^- annihilation with center-of-mass energy $2E_{\text{beam}} = 10.6$ GeV. If we set $v^2 \approx 0.3$, $\alpha_s \approx 0.2$, and $m_c \approx 1.4$ GeV, we obtain the naive estimate $R[J/\psi + \eta_c] \approx 4 \times 10^{-7}$. This should be compared with the total ratio $R[\text{hadrons}] \approx 3.6$ for all hadronic final states [21].

Because the two charmonia in the final state have opposite charge-conjugation quantum numbers, it is as-

TABLE I: Cross sections in fb for e^+e^- annihilation into double-charmonium states $H_1 + H_2$ at $E_{\text{beam}} = 5.3$ GeV without relativistic corrections. The errors are only those from variations in the NLO pole mass $m_c = 1.4 \pm 0.2$ GeV. From Ref. [16].

$H_2 \setminus H_1$	J/ψ	$\psi(2S)$
η_c	2.31 ± 1.09	0.96 ± 0.45
$\eta_c(2S)$	0.96 ± 0.45	0.40 ± 0.19
$\chi_{c0}(1P)$	2.28 ± 1.03	0.95 ± 0.43

sumed that they are produced by a single virtual photon. The four QCD diagrams for the color-singlet process $\gamma^* \rightarrow c\bar{c}_1 + c\bar{c}_1$ are shown in Fig. 1. We take the upper $c\bar{c}$ pair in Fig. 1 to form a $C = -$ charmonium H_1 with momentum P_1 and the lower $c\bar{c}$ pair to form a $C = +$ charmonium H_2 with momentum P_2 . There are also QED diagrams for $\gamma^* \rightarrow c\bar{c}_1 + c\bar{c}_1$ that can be obtained from the QCD diagrams in Fig. 1 by replacing the virtual gluons by virtual photons, but they are suppressed by a factor of α/α_s . However if one of the charmonia is a 1^{--} state, such as a J/ψ , then there are the additional QED diagrams in Fig. 2. Although they are also suppressed by a factor of α/α_s , they are enhanced by a kinematic factor of $1/r^2$, where the variable r is defined by

$$r^2 = \frac{4m_c^2}{E_{\text{beam}}^2}, \quad (2)$$

and therefore can be more important than one might expect.

The $\alpha^2\alpha_s^2$ term in the cross section for $e^+e^- \rightarrow J/\psi + \eta_c$ was calculated previously by Brodsky and Ji [23]. They presented their result in the form of a graph of R versus $1/r^2$, but they did not give an analytic expression for the cross section. Our predictions for the double-charmonium cross sections without relativistic corrections are given in Table I. The error bars are those associated with the uncertainty in the NLO pole mass m_c only. The relativistic corrections increase the central values of the cross sections by about 2.4 for $J/\psi + \eta_c$, by about 6 for $J/\psi + \eta_c(2S)$ and $\psi(2S) + \eta_c$, and by about 13 for $\psi(2S) + \eta_c(2S)$. Although the total correction factor for $J/\psi + \eta_c$ is significantly larger than 1, it is the product of several modest correction factors that all go in the same direction [16].

The BELLE Collaboration has recently measured the cross section for $J/\psi + \eta_c$ [14]. The J/ψ was detected through its decays into $\mu^+\mu^-$ and e^+e^- , which have a combined branching fraction of about 12%. The η_c was observed as a peak in the momentum spectrum of the J/ψ corresponding to the 2-body process $J/\psi + \eta_c$. The measured cross section is

$$\sigma[J/\psi + \eta_c] \times B[\geq 4] = (33_{-6}^{+7} \pm 9) \text{ fb}, \quad (3)$$

where $B[\geq 4]$ is the branching fraction for the η_c to decay

into at least 4 charged particles. Since $B[\geq 4] < 1$, the right side of Eq. (3) is a lower bound on the cross section for $J/\psi + \eta_c$. Updated BELLE cross section is even larger than that given in Eq. (3) [22].

The lower bound provided by Eq. (3) is about an order of magnitude larger than the central value 2.3 fb of the calculated cross section for $J/\psi + \eta_c$ in Table I. The largest theoretical errors are QCD perturbative corrections, which we estimate to give an uncertainty of roughly 60%, the value of m_c , which we estimate to give an uncertainty of roughly 50%, and a relativistic correction that we have not been able to quantify with confidence.

In Ref. [16], we considered various two-charmonium processes in which the charmonia have opposite C-parity. Complete helicity amplitudes for those processes are also presented in Ref. [16]. Liu, He, and Chao also calculated the $\alpha^2\alpha_s^2$ terms in the cross sections for e^+e^- annihilation into $J/\psi + H$, $H = \eta_c, \chi_{c0}, \chi_{c1}$, and χ_{c2} [17]. Their results are consistent with ours.

One might suspect that the discrepancy between theory and experiment exists because of some problem in NRQCD factorization approach. Substituting the input parameters used in above analysis into the formula for the rate that is derived from light-front method in Ref. [23], we find the result exactly agrees with that from NRQCD [24]. This implies that the discrepancy is not from NRQCD, but from pQCD factorization itself.

III. EXCLUSIVE DOUBLE- J/ψ PRODUCTION

Having no conclusive idea for filling the huge gap between the data and theory with perturbative corrections, we began to question whether the BELLE signal consists entirely of $J/\psi + \eta_c$ events. As a possibly missing contribution, Bodwin, Braaten, and I considered e^+e^- annihilation into double- J/ψ states that have the same charge-conjugation parity (C-parity) [18, 19]. The strongest motivation was the observation that the width of the η_c signal measured by the BELLE Collaboration is similar to the mass difference between J/ψ and η_c . In the BELLE fit to the J/ψ momentum distribution, the full width at half maximum of the η_c peak is about 0.11 GeV. Since the mass difference between the J/ψ and η_c is about 0.12 GeV, there are probably $J/\psi + J/\psi$ events that contribute to the $J/\psi + \eta_c$ signal that is observed by BELLE.

This process proceeds, at leading order in the QCD coupling α_s , through QED diagrams, shown in Fig. 3, that contain two virtual photons. One might expect that these cross sections would be much smaller than those for charmonia with opposite C-parity because they are suppressed by a factor of α^2/α_s^2 . However, if both charmonia have quantum numbers $J^{PC} = 1^{--}$, then there is a contribution to the cross section in which each photon fragments into a charmonium [18, 19]. The fragmentation contribution is enhanced by powers of $1/r$ [18, 19]. A similar, but less dramatic, example is the non-negligible QED contribution shown in Fig. 2 for $e^+e^- \rightarrow \gamma^* \rightarrow$

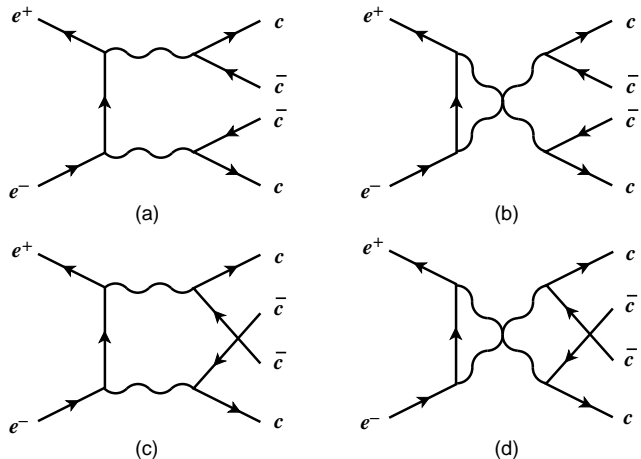


FIG. 3: QED diagrams for the process $e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow c\bar{c}_1 + c\bar{c}_1$. The upper and lower $c\bar{c}$ pairs evolve into H_1 and H_2 , respectively.

$J/\psi + \eta_c$ process. This enhancement can compensate for the suppression factor that is associated with the coupling constants.

The photon-fragmentation contributions shown in Figs. 3(a) and 3(b) are enhanced because the virtual-photon propagators are of order $1/m_c^2$ instead of order $1/E_{\text{beam}}^2$. In the amplitude, there are also two numerator factors of m_c instead of E_{beam} , which arise from the $c\bar{c}$ electromagnetic currents. Hence, the net enhancement of the squared amplitude is $1/r^4$, and the contributions to R can be nonzero in the limit $r \rightarrow 0$. As $r \rightarrow 0$ with fixed scattering angle θ , the photon-fragmentation contributions to the cross section factor into the cross section for $e^+e^- \rightarrow \gamma\gamma$ with photon scattering angle θ and the fragmentation probabilities for $\gamma \rightarrow H_1$ and $\gamma \rightarrow H_2$. These fragmentation probabilities are nonzero at order α only for $J^{PC} = 1^{--}$ states with helicities satisfying $\lambda_1 = -\lambda_2 = \pm 1$. The contribution to the ratio R for $J/\psi + J/\psi$ has the behavior

$$R[J/\psi(\lambda_1) + J/\psi(\lambda_2)] \sim \alpha^2(v^2)^3, \quad (4)$$

where $\lambda_1 = -\lambda_2 = \pm 1$. This asymptotic behavior can be compared with that for $J/\psi + \eta_c$:

$$R[J/\psi + \eta_c] \sim \alpha_s^2(v^2)^3(r^2)^3, \quad (5)$$

which holds generally for S -wave final states with opposite C-parity. In this case, an additional factor r^2 arises from helicity suppression. The ratio R in Eq. (4) is suppressed relative to Eq. (5) by a factor of $(\alpha/\alpha_s)^2 \approx 10^{-3}$, but the enhancement factor that scales as r^{-6} makes the cross sections comparable in magnitude at the energy of a B factory. In addition, the differential cross section has a sharp peak in both forward and backward regions owing to the subprocess $e^+e^- \rightarrow \gamma\gamma$, which results in another enhancement factor $\ln(8/r^4)$ in the integrated cross section.

The differential cross section for exclusive double- J/ψ production as a function of $x = \cos \theta$ is shown in Fig. 4.

TABLE II: Cross sections in fb for e^+e^- annihilation at $E_{\text{beam}} = 5.3$ GeV into double-charmonium states $H_1 + H_2$ with $C = -1$. The errors are only those from variations in the pole mass $m_c = 1.4 \pm 0.2$ GeV. There are additional large errors associated with perturbative and relativistic corrections, as discussed in the text. From Ref. [18, 19].

$H_2 \setminus H_1$	J/ψ	$\psi(2S)$
J/ψ	8.70 ± 2.94	7.22 ± 2.44
$\psi(2S)$		1.50 ± 0.51

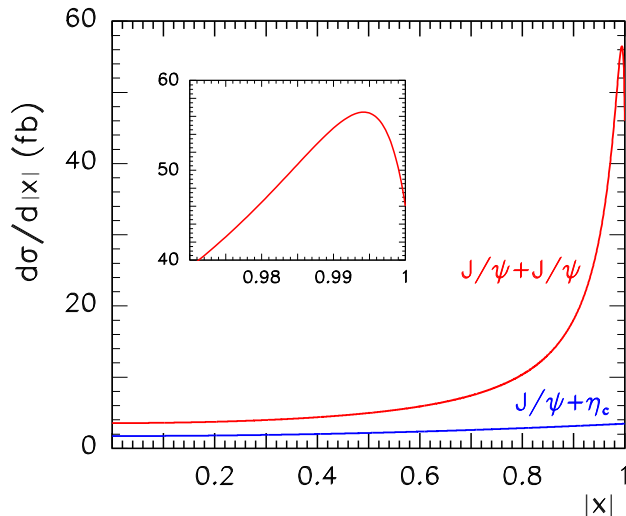


FIG. 4: Differential cross sections $d\sigma/d|x|$ for e^+e^- annihilation at $E_{\text{beam}} = 5.3$ GeV into $J/\psi + J/\psi$ and $J/\psi + \eta_c$. There are large errors associated with perturbative and relativistic corrections, as discussed in the text. From Ref. [18, 19].

Our predictions for double-charmonium cross sections are given in Table II for $C = -1$ states. The error bars are those associated with the uncertainty in the pole mass m_c only. The cross sections for the 1^{--} states are dominated by the photon-fragmentation diagrams in Figs. 3(a) and 3(b). For $m_c = 1.4$ GeV, they contribute 87.5% of the $J/\psi + J/\psi$ cross section. The nonfragmentation diagrams in Figs. 1(c) and 1(d) contribute 0.7%, while the interference term contributes 11.8%.

The perturbative corrections to the cross section for $J/\psi + J/\psi$ have not yet been calculated. However the perturbative corrections to the dominant photon-fragmentation diagrams in Figs. 3(a) and 3(b) are closely related to the perturbative correction to the electromagnetic annihilation decay rate for $J/\psi \rightarrow e^+e^-$, which gives a multiplicative factor

$$\left(1 - \frac{8}{3} \frac{\alpha_s}{\pi}\right)^2. \quad (6)$$

The perturbative correction to the photon-fragmentation terms in the cross section for $J/\psi + J/\psi$ is just the square of the expression (6). If we choose the QCD coupling constant to be $\alpha_s = 0.25$, which corresponds to a renormal-

ization scale $2m_c$, then the perturbative correction yields a multiplicative factor $(0.79)^4 = 0.39$. The same perturbative correction factor applies to the cross sections for $J/\psi + \psi(2S)$ and $\psi(2S) + \psi(2S)$. This perturbative correction factor applies only to the leading contributions to the cross sections in the limit $r \rightarrow 0$. However, since these contributions are dominant, we conclude that the perturbative corrections are likely to decrease the cross sections by about a factor of 3.

The relativistic corrections to the $J/\psi + J/\psi$ cross section are significantly smaller than and have the opposite sign from the relativistic corrections to the $J/\psi + \eta_c$ cross section, which are given in Ref. [16]. The relativistic correction to the fragmentation process is 0.78. For $m_c = 1.4$ GeV, the relativistic corrections to the $J/\psi + \eta_c$ cross section are estimated to increase the cross section by about a factor 5.5. The large difference in the relativistic corrections suggests that there may be large relativistic corrections not only to the absolute cross sections for double-charmonium production, but also to the ratios of those cross sections.

If we take into account both perturbative and relativistic corrections, then the predicted cross section for $J/\psi + J/\psi$ at the B factories is of the same order of magnitude as that for $J/\psi + \eta_c$. After this proposal was made, the BELLE Collaboration looked for the predicted double- J/ψ events. Unfortunately, they did not find such events [25]. The non-observation of double- J/ψ events strongly suggests there is something wrong in our understanding of factorization in quarkonium production or of the relevant production mechanisms. If the factorization formalism is valid and we have accounted for the dominant production mechanisms, then there is no reason why $J/\psi + \eta_c$ events should be seen while double- J/ψ events are not. Note that the two production processes depend on essentially the same non-perturbative factor. At the moment, we know the relativistic correction seems to have an important role in increasing the cross sections for $J/\psi + \eta_c$ [16]. The corrections to the two-charmonium processes in next-to-leading order in the strong coupling constant are still unknown. The NLO result may help us with pinning down the origin of the problem.

IV. EXCLUSIVE J/ψ -GLUEBALL PRODUCTION

The cross sections for $J/\psi + \eta_c$, χ_{c0} , and $\eta_c(2S)$ recently measured by the BELLE Collaboration are not well understood within pQCD or within NRQCD factorization. If there is nothing wrong in our factorization formula, then the BELLE signal must include something else that we have not considered. The non-observation of double- J/ψ events strongly suggests there is something other than η_c in the signal. This follows from the fact that the non-observation of double- J/ψ events in the current BELLE data is still consistent with the theoretical predictions for the absolute double- J/ψ cross

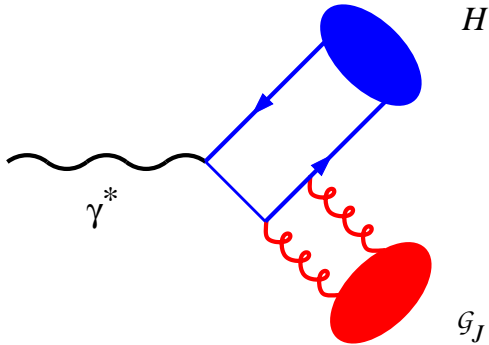


FIG. 5: Feynman diagram for $\gamma^* \rightarrow H + \mathcal{G}_J$.

section. On the basis of this observation, Brodsky, Goldhaber, and I argued that the signal may include events in which there is exclusive J/ψ production associated with a $J^{PC} = J^{++}$ glueball \mathcal{G}_J with $J = 0, 2$ [20].

Bound states of gluons provide an explicit signature of the non-Abelian interactions of quantum chromodynamics. In fact, in a model universe without quarks, the hadronic spectrum of QCD would consist solely of color-singlet glueball states. According to a recent lattice calculation by Morningstar and Peardon [26], the ground-state masses for the $J^{PC} = 0^{++}$ and 2^{++} glueballs \mathcal{G}_J are 1.73 and 2.40 GeV, respectively. There are many excited states in the mass range of charmonium spectrum [26].

The cross section for $e^+e^- \rightarrow J/\psi + \mathcal{G}_J$ might not be suppressed compared with cross sections for exclusive quarkonium pairs such as $\gamma^* \rightarrow J/\psi + \eta_c$ that arise from the subprocess $\gamma^* \rightarrow (c\bar{c}) + (c\bar{c})$. That is because the subprocesses $\gamma^* \rightarrow (c\bar{c}) + (c\bar{c})$ and $\gamma^* \rightarrow (c\bar{c}) + (gg)$ are of the same nominal order in pQCD. Thus, it is possible that some portion of the signal observed by BELLE in $e^+e^- \rightarrow J/\psi + X$ may actually be due to the production of $J/\psi + \mathcal{G}_J$ pairs.

The amplitude for $e^+e^- \rightarrow J/\psi + \mathcal{G}_J$ at leading twist can be expressed as a factorized product of the perturbative hard-scattering amplitude $T_H(\gamma^* \rightarrow Q\bar{Q} + gg)$ convoluted with the nonperturbative distribution amplitudes for the heavy quarkonium and glueball states. A bound on the normalization of the distribution amplitude for the glueball state can be extracted from a resonance search by CUSB in $\Upsilon \rightarrow \gamma + X$ [27] following the method used in Ref. [28].

Our predictions for the upper limits to the exclusive charmonium-glueball production cross sections are given in Table III. We find that the upper limit to the cross

section $\sigma_{J/\psi\mathcal{G}_0}$ is comparable to the NRQCD prediction of the cross sections for $e^+e^- \rightarrow J/\psi + H$ for $H = \eta_c$ and χ_{c0} , and larger by factor 2 than that for $H = \eta_c(2S)$, suggesting the possibility that a significant fraction of the anomalously large cross section measured by BELLE may be due to glueballs in association with J/ψ production.

TABLE III: Upper limits to the cross section $\sigma_{J/\psi\mathcal{G}_0}$ and the ratio $\sigma_{J/\psi\mathcal{G}_0}/\sigma_{J/\psi H}$ at $\sqrt{s} = 10.6$ GeV, assuming that $M_{\mathcal{G}_0} = M_h$, where $H = \eta_c, \chi_{c0}$, and $\eta_c(2S)$. The limits are determined by the $\Upsilon \rightarrow \gamma X$ search of the CUSB Collaboration [27]. From Ref. [20].

$M_{\mathcal{G}_0} = M_h$	$h = \eta_c$	χ_{c0}	$\eta_c(2S)$
$\sigma_{J/\psi\mathcal{G}_0}^{\max}$	1.4 fb	1.5 fb	1.6 fb
$\sigma_{J/\psi\mathcal{G}_0}^{\max}/\sigma_{J/\psi h}$	0.63	0.72	1.9

V. DISCUSSION

The anomalously large cross section for exclusive $J/\psi + \eta_c$ production measured by the BELLE Collaboration is not well understood within pQCD factorization or within the NRQCD factorization formalism. If the BELLE signals are made purely of $J/\psi + \eta_c$ events, then either pQCD factorization fails or there are important production mechanisms that we have not yet taken into account. The former possibility would be a violation of an established pQCD factorization theorem. If the exclusive two-charmonium production process is demonstrated to violate the factorization theorem, then one must understand why. Without a fundamental understanding this problem, one can not safely use such factorization theorems, which are a central part of most current particle phenomenology.

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